Gluon Polarization and Dihadron Production at RHIC

Guanghua Xu
University of California, Riverside, CA 92521

J. C. Peng
Los Alamos National Laboratory, Los Alamos, NM 87545

1. Introduction

Recent Deep Inelastic Scattering (DIS) experiments have indicated that gluons may play an important role in the spin structure of the proton. As an electromagnetic process, the DIS is not directly sensitive to the neutral gluons. In contrast, polarized p-p collisions at RHIC offers an opportunity to probe the gluon distributions via strong interaction processes. Indeed, one of the main goals of the RHIC-spin physics program is to determine the spin-dependent gluon structure functions. The processes sensitive to the gluon structure functions include direct-photon production, open-charm production, and jet poduction. Although the process of dijet production in hadron-hadron collisions have been studied in the literature [1], a closely related process, namely the high-mass dihadron production, has received little attention so far. The purpose of this note is to discuss the feasibility of using dihadron production at RHIC to extract information on the spin-dependent gluon structure functions.

For dijet and dihadron production, subprocesses involving quark-quark, quark-gluon and gluon-gluon scatterings can all contribute to the observed cross sections and double helicity asymmetries. To distinguish the effects of gluons from those of quarks, it is important to identify the kinematic region where gluon subprocesses play a dominant role. After identifying the region where gluon dominates, it is necessary to check how sensitively the measurements can separate different parametrizations of gluon stucture functions.

In Section 2, we present the formula and calculations for the cross sections and double helicity asymmetries for both the dijet and the dihadron productions. The expected sensitivity of dihadron measurement at PHENIX for distinguishing various parametrizations of the spin-dependent gluon structure functions will be presented in Section 3. Summary and future prospect will be given in Section 4.

2. Dijet and Dihadron Productions in Hadron-Hadron Collisions

Consider two jets produced with rapidities y_1 and y_2 and with equal and opposite transverse momentum p_T. The differential cross section and the double helicity asymmetry A_{LL} can be written as[1]

$$\frac{d^3\sigma}{dM\,dy_1 dy_2} = \frac{M^3}{2s\cdot cosh^2 y^*}\sum_{a,b}\frac{1}{1+\delta_{ab}}\cdot$$

$$[f_A^a(x_A,Q^2)f_B^b(x_B,Q^2)\frac{d\hat{\sigma}_{ab}}{d\hat{t}}(\hat{s},\hat{t},\hat{u})+(a\leftrightarrow b)], \tag{1}$$

$$A_{LL} = (\frac{d^3\sigma}{dM\,dy_1 dy_2})^{-1}\frac{M^3}{2s\cdot cosh^2 y^*}\sum_{i,j}\frac{1}{1+\delta_{ab}}\cdot$$

$$[\Delta f_A^a(x_A,Q^2)\Delta f_B^b(x_B,Q^2)\hat{a}_{LL}^{ab}\frac{d\hat{\sigma}_{ab}}{d\hat{t}}(\hat{s},\hat{t},\hat{u})+ (a\leftrightarrow b)], \tag{2}$$

where

$$M = 2p_T cosh y^*, \quad Q^2 = p_T^2/4,$$
$$x_A = \sqrt{\tau}e^{y}, \quad x_B = \sqrt{\tau}e^{-y}, \tag{3}$$

with

$$\tau = \frac{M^2}{s},$$
$$y^* = \frac{1}{2}(y_1 - y_2), \qquad y = \frac{1}{2}(y_1 + y_2). \tag{4}$$

In Eqs. 1 and 2 the $d\hat{\sigma}_{ab}/d\hat{t}$ and $\hat{a}_{LL}^{ab}$ are the cross section and the double helicity asymmetry of the hard scattering subprocesses[1], and $f_A^a(x_A,Q^2)$ and $\Delta f_A^a(x_A,Q^2)$ are spin-averaged and spin-dependent structure functions of parton a in hadron A. We will use the structure functions given by Gehrmann and Stirling (G-S) [2], which reproduce the DIS data well, as the inputs to our calculations. The $d^3\sigma/dM dy_1 dy_2$ and A_{LL} versus the jet-pair mass M at $y_1 = y_2 = 0$ and $\sqrt{s} = 500GeV$ are shown in Figs. 1(a) and 1(b), respectively.

Fig. 1 shows that the gluon-gluon scattering process dominates at most kinematic region. This is due to the facts that: (i) $(d\hat{\sigma}/d\hat{t})_{gg}$ is significntly larger than other processes, e.g. $(d\hat{\sigma}/d\hat{t})_{gg\to gg}$: $(d\hat{\sigma}/d\hat{t})_{qq\to qq}$: $(d\hat{\sigma}/d\hat{t})_{q\bar{q}\to q'\bar{q}'}$ = 30.4 : 3.26 : 0.22 at $\theta = 90°$. (ii) $(\hat{a}_{LL})_{gg\to gg}$ has a large positive value ($(\hat{a}_{LL})_{gg\to gg} = 0.77$ at $\theta = 90°$). (iii) gluons are more abundant than the quarks at the relatively small x region ($x \lesssim 0.3$) explored at RHIC. Therefore, as long as ΔG is not too small, we would expect important contributions to A_{LL} from gluon-gluon scatterings.

As the rapidity of the dijet increases, our calculations show that the quark-gluon scattering process becomes increasingly important. Hence, by choosing a small polar angle θ (which corresponds to a large dijet rapidity), one can detect dijets which are sensitive to the valence quark distributions. More detailed discussion on the rapidity dependence of dijet production will be presented elsewhere [3].

To examine the sensitivity of dijet production to spin-dependent gluon structure functions, we show in Fig. 1(c) the double helicity asymmetries using three different G-S parametrizations[2] (sets A, B, and C). As shown in Fig. 1(c), different $\Delta G(x, Q^2)$ gives very different A_{LL}, suggesting that dijet production can be used to distinguish different parametrizations for the gluon polarization.

The cross section and double helicity asymmetry for dihadron production in hadron-hadron collisions (A+B → C+D+X) are given by[3,4]

$$\frac{d^3\sigma}{dM dy_1 dy_2} = \frac{2x_{T_1}x_{T_2}}{coshy^*}\int_{p_{T_{min}}}^{p_{T_{max}}} dp_T \sqrt{\frac{p_T^C p_T^D}{(p_T^C)^2+(p_T^D)^2}} \int_{z_{min}}^{z_{max}} \frac{dz_C}{z_C^3} \sum_{a,b} f_A^a(\frac{x_{T_1}}{z_C}, Q^2) f_B^b(\frac{x_{T_2}}{z_C}, Q^2) D_c^C(z_C) D_d^D(z_D) \frac{d\hat{\sigma}_{ab}(a+b\to c+d)}{d\hat{t}}, \tag{5}$$

$$A_{LL} = (\frac{d^3\sigma}{dM dy_1 dy_2})^{-1} \frac{2x_{T_1}x_{T_2}}{coshy^*}\int_{p_{T_{min}}}^{p_{T_{max}}} dp_T \int_{z_{min}}^{z_{max}} \frac{dz_C}{z_C^3} \sqrt{\frac{p_T^C p_T^D}{(p_T^C)^2+(p_T^D)^2}} \sum_{a,b} \Delta f_A^a(\frac{x_{T_1}}{z_C}, Q^2) \Delta f_B^b(\frac{x_{T_2}}{z_C}, Q^2) \hat{a}_{LL}^{ab} \frac{d\hat{\sigma}_{ab}(a+b\to c+d)}{d\hat{t}} D_c^C(z_C) D_d^D(z_D), \tag{6}$$

with

$$M = 2\sqrt{p_T^C p_T^D}coshy^*, \quad Q^2 = \frac{(p_T^C)^2}{4z_C^2}$$
$$x_{T_1} = \frac{p_T^C}{\sqrt{s}}(e^{y_1}+e^{y_2}), \quad x_{T_2} = \frac{p_T^C}{\sqrt{s}}(e^{-y_1}+e^{-y_2})$$
$$p_T = |p_T^D| - |p_T^C|, \quad z_D = z_C|p_T^D/p_T^C|,$$
$$z_{min} = max(x_{T_1}, x_{T_2}),$$
$$z_{max} = \begin{cases} 1 & \text{if } |p_T^D/p_T^C| < 1 \\ |p_T^C/p_T^D| & \text{if } |p_T^D/p_T^C| > 1 \end{cases} \tag{7}$$

where $d\hat{\sigma}_{ab}/d\hat{t}$, $\hat{a}_{LL}^{ab}$, $f_A^a(x, Q^2)$ and $\Delta f_A^a(x, Q^2)$ have the same definitions as in the dijet case, and $(p_{T_{min}}, p_{T_{max}})$ specifies the range of the net p_T of the dihadron. $D_c^C(z)$ and $D_d^D(z)$ are the fragmentation functions describing the probability for a parton to hadronize into a hadron carrying a fraction z of the parton momentum.

If we integrate over y_1 and y_2, Eq. 5 can be written as

$$\frac{d\sigma}{dM} = \int_{-Y}^{Y} dy_1 \int_{y_{min}}^{y_{max}} dy_2 \frac{d^3\sigma}{dM dy_1 dy_2}, \tag{8}$$

and a similar expression for A_{LL}. The rapidity coverage for the detector is from $-Y$ to Y, and

$$y_{min} = max(-Y, ln\frac{M^2}{s} - y_1),$$
$$y_{max} = min(Y, -y_1 - ln\frac{M^2}{s}). \tag{9}$$

We have calculated the differential cross section and double helicity asymmetry A_{LL} for π^0-pair production in p-p collision. We chose π^0-pair production in our study for two reasons. First, the detection of π^0 is relatively straightforward since it only requires electromagnetic calorimeter. Second, there exist some π^0-pair production data from ISR [5] and our calculations can be compared with these data.

Using the structure functions of [2] and the fragmentation functions given in [6], we calculated the differential cross section $d^3\sigma/dM dy_1 dy_2$ and A_{LL} for π^0-pair production in p-p collision at $y_1 = y_2 = 0$ and $\sqrt{s} = 500GeV$ for $|p_T| < 1GeV/c$. The results are shown in Figs. 2(a) and 2(b). Comparing Fig. 2 with Fig. 1, one observes similar shapes for A_{LL} in dijet and dihadron productions. However, the predicted A_{LL} is shifted towards lower dihadron mass M for dihardon production versus dijet production. In other words, there appears to be a correspondence between the dijet production at a given M and the dihadron productions at a lower M.

This approximate correpondence between dijet and dihadron productions can be understood by considering the simple case of $y_1 = y_2 = 0$ and the net dihadron $p_T = 0$. We find $M_{dihadron} \sim \bar{z} M_{dijet}$, where $\bar{z}$ is the mean value of z, and the dihadron production is sampling the x region very similar to that of the dijet production. This rough correpondence between dijet and dihadron productions has an important implication, namely, information which are obtained from high-M dijet measurement can already be obtained in dihadron measurement at significantly lower M.

To check the sensitivity of dihadron production to the gluon polarization, we show in Fig. 2(c) the predictions for A_{LL} for the three G-S $\Delta G(x, Q^2)$ parametrizations.[2] The results indicate good sensitivity to the spin-dependent gluon structure functions just like the case for dijet production. This is to be expected given the rough correpondence property discussed above.

An extensive study of π^0-pair production in pp collisions has been performed at ISR by the CCOR collaboration.[5] In Fig. 3, we compare our calculations with the CCOR data. Note that a normalization factor of 2.5 has been applied to the calculations. This normalization factor is reminiscent of the K-factor in the Drell-Yan process and it reflects additional contributions from higher-order processes to the dihadron productions. The mass and the $\sqrt{s}$ dependences of the CCOR data are well reproduced by our calculations.

3. Dihadron Productions at PHENIX

In this Section, we consider the expected rates and sensitivities for measuring π^0-pair productions using the PHENIX detector at RHIC.

RHIC can accelerate polarized proton beams up to $\sqrt{s} = 500GeV$ at the luminosity of $2 \times 10^{32} \times (\sqrt{s}/500)cm^{-2}sec^{-1}$ with large polarization of 70%. In the following studies, we will assume the integrated luminosity of $800pb^{-1}$ for $\sqrt{s} = 500GeV$, which corresponds to 10 weeks of running time.

The azimuthal acceptance for PHENIX detectors is about 135°. For net $p_T < 1GeV/c$, and $\Delta y_1 = \Delta y_2 = 0.15$ around $y_1 = y_2 = 0$, we show in Fig. 2(c) the expected statistical errors for a 10-week run. The dihadron measurements can clearly separate the three ΔG's given in [2].

If we integrate over the polar angles corresponding to the PHENIX acceptance in pseudo rapidity, $-0.35 < \eta < 0.35$, the expected yields for π^0-pair production are listed in the following (where the unit of M is GeV/c^2):

Kinematic Range	Yield
$8 < M < 12$	$\sim 5.0 \times 10^6$
$12 < M < 16$	$\sim 6.1 \times 10^5$
$16 < M < 36$	$\sim 1.7 \times 10^5$
$36 < M < 52$	$\sim 1.2 \times 10^3$

The sensitivity of this measurement to the three ΔG's is shown in Fig. 4. The integration over the polar angles will smear out the kinematic region x for a given M, but better statistics will be obtained for distinguishing the three ΔG's.

As seen from Fig. 2(c) and Fig. 4, one can distinguish the three ΔG's quite well at least up to $M \simeq 20GeV/c^2$, which corresponds to $x \simeq 0.13$. For distinguishing the three ΔG's at higher M, more statistics is needed.

4. Summary and Future Prospect

We would summarize the above discussions as follows:

1. Dihadron and dijet productions at RHIC are sensitive to gluon structure functions.

2. A rough correspondence exists between dihadron and dijet productions. This feature makes it possible to use dihadron production as an alternative method to study spin-dependent gluon structure functions.

3. A two-month measurement for π^0-pair production at PHENIX could clearly distinguish the various Gehrmann and Stirling polarized gluon structure functions.

4. Further studies are required to investigate the sensitivity of these results to fragmentation functions, and to extend the investigation to other dihadron channels such as $\pi^+\pi^-$.

Acknowledgements

We would like to thank Dr. Joel Moss of LANL and Dr. Mike Tannenbaum of BNL for valuable discussions.

[1] C. Bourrely et al., Phys. Rep. **177** (1989) 319.

[2] T. Gehrmann and W.J. Stirling, Phys. Rev. D **53** (1996) 6100.

[3] G. Xu and J. C. Peng, to be published.

[4] R. Baier et al., Z. Physik C, Particles and Fields **2** (1979) 265.

[5] A.L.S. Angelis et al., Nucl. Phys. B **209** (1982) 284.

[6] P. Chiappetta et al., Nucl. Phys. B **412** (1994) 3.

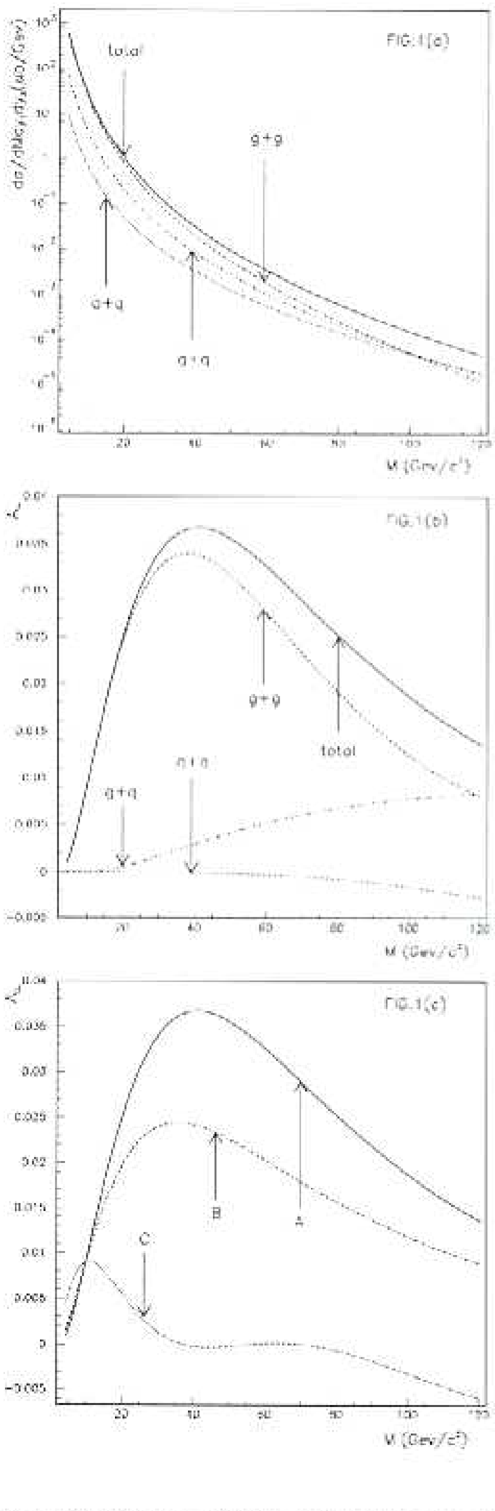

FIG. 1. Calculations of dijet productions in p-p collisions at $\sqrt{s} = 500 GeV$ and $y_1 = y_2 = 0$. (a) and (b) show the contributions from various subprocesses to the cross section and double helicity asymmetry, and (c) shows the A_{LL} using three sets of parametrizations of gluon polarization given in [2].

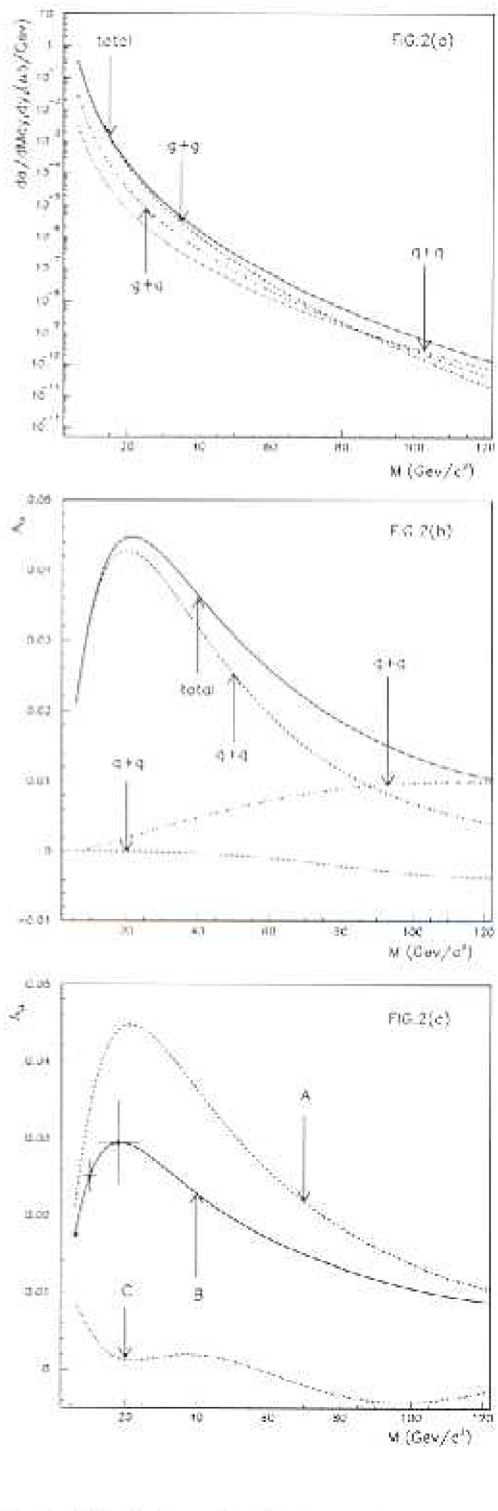

FIG. 2. Calculations of π^0-pair productions in p-p collisions at $\sqrt{s} = 500 GeV$ and $y_1 = y_2 = 0$. (a) and (b) show the contributions from various subprocesses to the cross section and double helicity asymmetry, and (c) shows the A_{LL} using three sets of parametrizations of gluon polarization given in [2] and the expected statistical errors for a $800 pb^{-1}$ run in PHENIX.

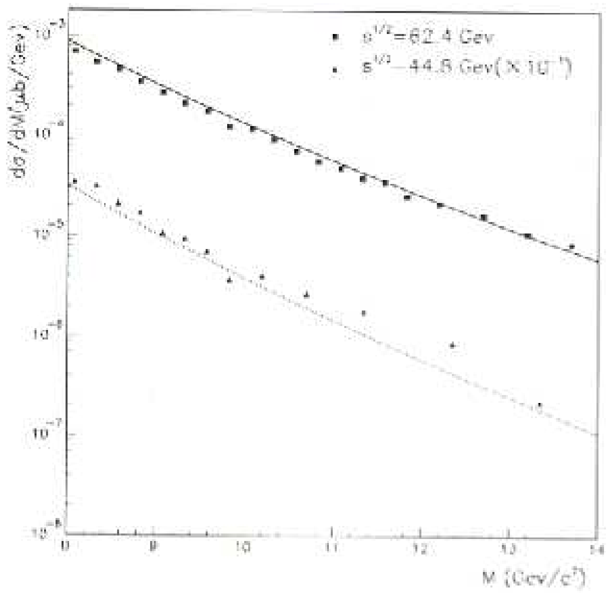

FIG. 3. Comparison between the calculations and the π^0-pair production data in p-p collision from CCOR[5] at $\sqrt{s}$ of 44.8 and 62.4 GeV. A normalization factor of 2.5 has been multiplied to the calculations at both energies.

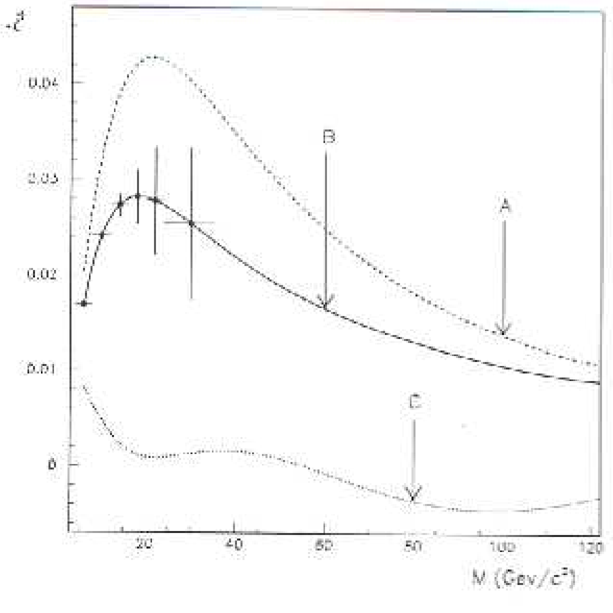

FIG. 4. Calculations of A_{LL} for π^0-pair detection at $\sqrt{s}$ = $500GeV$ integrated over the full acceptance of the PHENIX detector. The expected statistical errors for a $800pb^{-1}$ run are also shown